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CLASSIFICATION OF CLIMATES

BY C. E. P. BROOKS, D.SC.

The Greek philosophers, observing that the elevation of the sun at noon increased southwards and correctly inferring that this was the cause of the increasing heat, divided that part of the earth's surface which they knew into a series of parallel thermal zones, the most northerly and southerly being uninhabitable because of extreme cold and extreme heat. When instrumental observations began to accumulate in the mid nineteenth century, and climatologists turned again to the classification of climates, this thermal basis was still dominant.[1]* Thus A. Supan[2] (1879) limited the well known " torrid " and " frigid " zones by the mean annual temperature of 20°C. and the mean of 10°C. in the warmest month, and in 1884 W. Köppen's first classification[3] was on similar lines. Meanwhile botanists had likewise been defining zones based on the distribution of different types of plant assemblages, and had realised that between the tropical and temperate zones of humid vegetation, defined by temperature, must be inserted a " desert " zone, defined by lack of rainfall. The idea had also grown up that plants were natural " integrators " of all the climatic elements, especially temperature and moisture, and this led to a formula which tried to incorporate both these elements.

It was quickly realised that the moisture requirement of a plant is greater the higher the temperature. The ideal measure would be the difference between rainfall and free evaporation, but measurements of evaporation are too few and uncertain, and numerous attempts have been made to find an index which could be derived directly from the data readily available. As early as 1869 C. Linsser[4] had expressed the " effective rainfall " as the ratio P/T, where P is the annual precipitation in centimetres and T the mean annual temperature in degrees centigrade. W. Köppen, after experimenting with the numbers of rain days and the ratio of monthly rainfall to saturation deficit, settled down to a formula of the type $P/(aT + c)$, but the values of the constants have varied from one edition of his classification to another. Köppen also realised that the effectiveness of rainfall is greater if it falls in winter than in

*These numbers refer to the list of references on p. 100.

summer, and in 1923 he defined the limit of the steppe climate as $T + 22$ for winter rains, $T + 33$ for uniform rains and $T + 44$ for summer rains where T is in degrees Centigrade and the rainfall is in centimetres; the limits for the desert climate are half these amounts.

A slightly different approach was made by A. Ångström[5] in 1936, based on Van't Hoff's law that the velocity of a chemical reaction approximately doubles for each rise of temperature by 10°C. This gave a moisture coefficient

$$I = P/(1{\cdot}07)^t$$

Van't Hoff's law is of wide applicability in biological as well as chemical action, but in the former there is an optimum temperature above which the speed of action, e.g. rate of growth of plants, falls off.

In recent years the subject has been taken up in great detail by C. W. Thornthwaite[6] who, in 1931, defined " precipitation effectiveness " as

$$\frac{P}{E} = 11{\cdot}5\left(\frac{P}{T-10}\right)^{10/9}$$

where P is the precipitation in inches, E the evaporation in inches, and T the temperature in degrees Fahrenheit. In his latest contribution[7], however, Thornthwaite has discarded this form in favour of one which he regards as more logical. His classification has two main indices, which he terms " potential evapotranspiration " and " thermal efficiency ".

Potential evapotranspiration (P.E. or e) is the amount of water which would be used by the vegetation if it were available; it can be measured in a dry basin by finding the amount of irrigation water actually used, or in wetter regions by the difference between rainfall and run-off. In a standard month of 30 days with 12 hours possible sunshine it is given by

$$e = ct^a$$

the coefficients c and a being variable. The method is elaborate; it depends on the computation of a monthly index $i = (t/5)^{1{\cdot}514}$; the summation of the twelve values of i gives the annual heat index I. The coefficients a and c are complicated functions of I. The figures are then corrected for number of days and length of day in the months. The method is purely empirical, designed to fit the few actual measurements of e available in North America.

The basis of the moisture classification is the total balance $R - e$ and its variation throughout the year. He first finds the total surplus of water in the rainy months, and the total deficiency in the dry months, and expresses them in the form

$$I_h = \frac{100s}{n} \qquad I_a = \frac{100d}{n}$$

where s is the water surplus, d the water deficiency and n the water need. These are combined in the form

$$I_m = \frac{100s - 60d}{n}$$

the smaller coefficient of d taking account of the fact that in times of drought plants conserve moisture by reducing transpiration. I_m can range from above 100 to -60, and this range is divided into nine equal steps, A, B_4, B_3, B_2, B_1, C_2, C_1, D, E, from "perhumid" to "arid". Each of these is subdivided

into r, s, w, s_2, w_2, according as the deficiency of water occurs to a moderate or large extent in summer or winter.

The potential evapotranspiration is also an index of thermal efficiency, TE, and stations are again classified into nine TE stages from A′ (megathermal) to E′ (frost) according to the potential evapotranspiration with further subdivisions a′ to d′ according to the annual variation. The complete classification of a climate is therefore fourfold, e.g. San Francisco is $C_1B'_1s_2a'$ or " dry subhumid, first mesothermal, with large winter surplus and a temperature régime normal to megathermal ".

One of the most interesting features of the paper is the method of constructing diagrams of average water need by superposing curves of monthly potential evapotranspiration and monthly rainfall. Water is stored in the soil in times of excess, and drawn on in times of deficit, and Thornthwaite estimates this storage as equivalent to 4 in. (10 cm.) of rainfall, and this is shown in the diagrams. It may be of interest to construct such a diagram for Richmond (Surrey). This is shown in Fig. 1 where the broken line represents the precipitation, adjusted to a mean month of 30·5 days, and the full line the calculated potential evapotranspiration. Vertical shading represents the excess precipitation available for run-off, diagonal shading on the left the utilization of soil moisture and on the right the recharging of the soil. The inference from this diagram is that from mid May to the end of September there is less moisture available than plants can use, and surplus water is only available for run-off from early November to early April, a suprising conclusion. The total *e* for the year comes out as 25·3 in., which is considerably higher than either the evaporation from the tank or the difference between rainfall and run-off, both of which are about 15·5 in.

Actually, in a normal summer there is little or no water shortage in south-east England, and Thornthwaite's formula, developed for the United States, is evidently not applicable to this country without some modification. One source of the error probably lies in the correction for length of day which gives a multiplication factor of 1·37 for the calculated *e* in July. This is certainly too high, for in middle latitudes the greater length of the day in summer with increasing latitude cannot compensate for the lower elevation of the sun. Other sources of error are the amount of cloud at Richmond, which is only partially allowed for by the temperature factor, and the greater relative humidity in England compared with most of the United States.

Thornthwaite's method is interesting, and appears to represent a considerable advance in the calculation of the agricultural possibilities of different climates, but it is evident that he has not yet approached finality. One important element which he has overlooked is the spread of the rainfall over a month, i.e. the number of rain days. Four rainfalls each of 0·5 in. are generally much more effective in providing soil moisture than a single storm of 2-in. rainfall. On the other hand, in summer a number of very light falls do little good. The maximum effectiveness of a summer rainfall probably occurs with daily amounts between 0·25 and 0·75 in. while in winter the limits are lower. Any complete calculation of the water supply available for plants should take account of these facts, for example, by subtracting from the effective rainfall some proportion which depends on the average rainfall in a rainfall day.

The classification of climates grew up as a result of the study of the distribution of plant assemblages, and has also been applied successfully to the study of soil types. In both these cases the effect cannot be expressed numerically by a single figure, and therefore cannot be represented by isopleths. It requires description, and the climatic formula is a convenient shorthand for such a description. Mapping these shorthand descriptions appears to be the only convenient way of setting out the facts. It must be remembered however, that the boundaries between the types are in most cases not sharp lines but transitional areas, and that the more elements brought in, the greater is the complexity of the actual distribution, due to local conditions, and especially the slope and

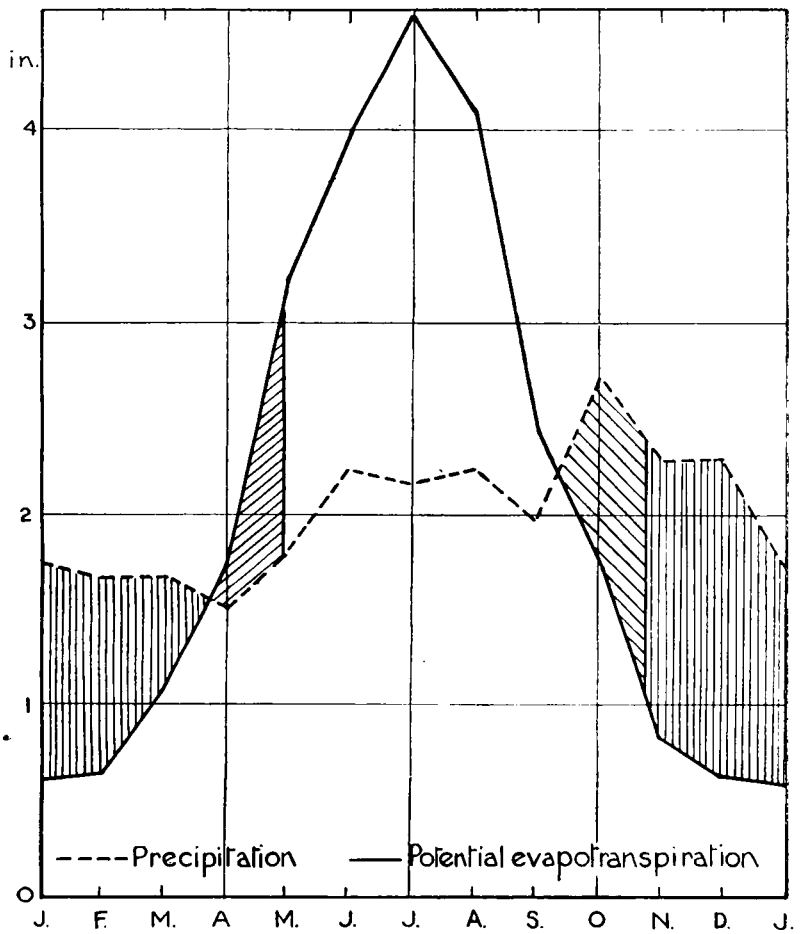

FIG. 1—MOISTURE DIAGRAM FOR RICHMOND, SURREY

aspect of the land. When it is possible to derive an expression which represents the combined effect of the climatic factors by a single number, as was done for example by Ellsworth Huntington for human energy, it is better to construct isopleths of the numerical values of that expression.

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SOME ASPECTS OF THE THEORY OF TURBULENCE

BY E. J. SUMNER, B.A.

Part II

Coefficient of eddy diffusivity.—In the foregoing analysis θ is any property which can be associated with an elementary volume of a fluid and which can be thought of as remaining invariant for a limited time following the motion. Also, quoting Brunt[1]*, it must be such that its upward flux has a physical meaning. In the atmosphere the " properties which appear to satisfy these conditions are content of water vapour, dust or carbon dioxide etc., momentum in a fixed azimuth, deviation of temperature from an adiabatic distribution." The expression eddy diffusivity can be used to designate the diffusion of any of these properties, but the processes by which momentum and temperature are transported are often distinguished by the terms eddy viscosity and eddy conductivity respectively.

At one time it was thought that the coefficient of eddy diffusivity K_θ was the same for all properties, and a certain amount of experimental data was forthcoming to support this, but some later evidence is against the hypothesis. As originally defined, K_θ is equal to $\overline{w'l_\theta}$, where l_θ is the transport length of the property in question, that is, the vertical distance moved by an element of fluid to a particular datum level from when it last had a value equal to the mean value of its environment. In the transfer of horizontal momentum, for example, the particle starts with a horizontal velocity equal to the mean velocity at its level, and it is improbable that it simultaneously has acquired the mean temperature, mean moisture content, etc., of its surroundings, so that l_θ would be expected to vary with θ. This does not necessarily mean that $\overline{w'l_\theta}$ depends on the property, but, to say the least, it strongly suggests that conclusion. If, on the other hand, the level of origin of a fluid element is defined as that at which the element was last at rest in the vertical, the transport length is now independent of θ, and may be written without the suffix.

In this case as before, see Part I, equation (5)

$$K_\theta = \overline{w'l} - \frac{\overline{w'\theta''}}{\delta\bar{\theta}/\delta z}, \text{ except when } \frac{\delta\bar{\theta}}{\delta z} = 0,$$
$$= K - K'_\theta, \text{ say.} \qquad \ldots (6)$$

*These numbers refer to the list of references on p. 108.

The value of the coefficient K $(= \overline{w'l})$ is the same for all properties and depends entirely on the dynamics of the eddies, whereas the second expression, K'_θ explicitly recognises the presence of the natural fluctuations in the property, and probably varies with θ. This separation of K_θ into two distinct terms is a definite improvement on the older theories, although there still remains the objection, common to all transport-length theories, that the dependence of l on molecular diffusion is ignored. The sign of K is always positive, while that of K'_θ, for a particular mean gradient, depends on the correlation between the eddy velocity of an element at a given level and of the anomaly of the property when it was last at rest in the vertical. The magnitude of the latter depends on the magnitude of the fluctuations of w' and θ'' and on the mean gradient $\delta\overline{\theta}/\delta z$. It is impossible to find the magnitude of θ'' by direct observation, and, for the time being, it will be assumed that its variations are of the same order of magnitude and similar in character to those of θ'.

The quantity $\overline{w'\theta''}$ is not measurable, but it is interesting to speculate on its possible value for different properties. Considering first of all the eddy conductivity, K_H say, then θ becomes $c_p(T + \Gamma z)$, where T is the absolute temperature, c_p the specific heat at constant pressure and Γ the dry adiabatic lapse rate. Since one would expect warmer parcels of air to show more inclination to rise than colder ones owing to buoyancy and *vice versa*, that is, for w' and T'' to have the same sign ($\overline{w'T''}$ positive), the sign of K'_H depends only on that of

$$\frac{\delta\overline{T}}{\delta z} + \Gamma.$$

For instability $\delta\overline{T}/\delta z$ is negative, and

$$\left|\frac{\delta\overline{T}}{\delta z}\right| > \Gamma,$$

so that the sign of K'_H is negative; and under stable conditions is positive.

This implies that $K_H > K$ for atmospheric instability, which is more often to be found near the ground in day-time, and $K_H < K$ for stability, the average state of the atmosphere away from the surface. For neutral equilibrium $K_H = K$ if sufficient time has elapsed to smooth out the anomalies ($K'_H = 0$). It is assumed throughout that no condensation takes place; for a saturated atmosphere Γ has to be replaced by the moist adiabatic lapse rate.

In the case of momentum transfer, the eddy viscosity, K_M say, is equal to $K - \overline{w'u''}/(\delta\overline{u}/\delta z)$ where u is the horizontal wind velocity. Unless eddies tend to rotate in one direction only it is obvious that there is no more reason why a particle of fluid should approach the datum surface from one direction rather than another, so that $\overline{w'u''}$ should be zero. Although no evidence one way or the other is available, it is suggested as a possibility that eddies do tend to rotate predominantly in one direction (like a wheel) close to the ground, where the horizontal cross-wind component of the mean vorticity $(\delta\overline{u}/\delta z)$ is invariably positive. If this is true, and a casual inspection of eddies revealed by smoke drifts suggests that it is, $\overline{w'u''}$ is negative, so that $K_M > K$, and one may hazard the guess that this remains true, on the average, throughout the troposphere, making $K_M > K > K_H$ away from the ground. On account of the inherently greater fluctuations (compared to the corresponding vertical gradient near the ground) of wind velocity than for temperature it is probable even here, that $K_M > K_H$, both being greater than K.

The diffusivity of other atmospheric properties depends on their correlation with those already discussed. Thus any θ which is positively correlated with the temperature T would also have the property that $K_\theta > K$ if its mean gradient, $\partial\bar{\theta}/\partial z$, were negative and *vice versa*. If the explanation, which is given later, of the origin of the fluctuations found in nature is correct, moisture content is such a property for diffusion near the ground. In the free air this correlation is probably very small, and one would expect K to be of the same order as K_θ both being greater than K_H. Summing up, all that can safely be said at the moment is that there are both practical and theoretical reasons for believing the coefficient of eddy viscosity to be greater than the coefficient of eddy conductivity everywhere in the atmosphere, and that eddy diffusivity for moisture content is intermediate in value, except possibly near the ground where it approaches the eddy conductivity and if anything is smaller than it. Petterssen and Swinbank[2] have found that the ratio of K_H to K_M in the free air is about 0·65 on an average, but the analysis on which the calculation is based is not rigorous enough to justify one accepting this value as final. K is, of course, not an absolute constant; it decreases rapidly as the atmosphere becomes more stable owing to decreases in both w' and l, as will be seen later.

The coefficient of eddy diffusivity is not directly measurable, but sufficient indirect evidence exists for a general understanding of its salient features. From a general point of view K_θ is determined by the character of the eddy motion, which includes the shape, size and frequency of the various eddies and their absolute and relative motion, an idea that is not amenable to mathematical analysis. It is known to increase rapidly with height above the ground, from a value very close to the coefficient of molecular diffusion to one thousands of times greater a few metres up. After a few hundred metres the rate of increase must fall off and ultimately its value probably decreases again. Its law of increase appears to be nearly linear from a few centimetres above the surface to a hundred metres or so, but it increases more rapidly than linearly in unstable atmospheres and less rapidly in inversions. The absolute value of the diffusivity also depends on the lapse of temperature, being very large for instability and very small for inversions, and it varies to a less extent with the surface roughness of the ground and with the mean wind velocity. This dependence of K_θ on circumstances has been known for a long time, but Priestley and Swinbank[3] have made the novel suggestion that the second term in equation (6) may entirely swamp the first in certain synoptic situations so that K_θ may occasionally be negative, that is, a property—especially, and perhaps only, in the case of temperature—may be transported against the gradient. As the authors point out, the average lapse of temperature away from the earth's surface is such that the potential temperature increases with height whereas mechanical turbulence, according to the earlier ideas, constitutes a powerful agency tending to equalise it. This, and other more factual evidence, which they produce, does support the idea. They go on to say that the approximate balance between the two terms of the flux equation " may account for the ability of radiative processes to dominate the heat transfer, and so achieve the isothermal state characteristic of the lower stratosphere, whereas mechanical turbulence would cause a decrease of temperature with height." At all events the coefficient of eddy diffusivity and the flux may be rather smaller in certain situations than considerations of temperature lapse, etc., would lead one to suppose.

Mass transport.—The atmosphere almost invariably contains solid and liquid particles, and if they are concentrated enough in a particular locality the process of eddy diffusion becomes visible. It is convenient to distinguish between the transport of mass (smoke, dust, spores, water and ice particles) and the less tangible entities previously discussed, in order to illustrate several points hitherto glossed over, and because there are some genuine differences. In the first place the particles may be sufficiently large to have a finite velocity of fall relative to the moving air, and the theory does not apply without modifications. One may instance the settling out of smuts and dust, or the extreme case of the formation of a hailstone. If the particles are small enough to remain in suspension, the transport-length approach is a very good approximation. It is not exactly true, however, since there will always be a small amount of relative motion between the air and the suspended matter, while the smallest particles will be subject to a Brownian movement analogous to molecular diffusion for the other properties.

It is, however, in considering the diffusion of a mass which originates in a limited space and whose rate of emission is independent of the state of the atmosphere, a smoke puff for example, that the main difficulty arises. Here, sideways diffusion is just as important as upwards diffusion and cannot be ignored. Another complication is the size of the cloud of particles, since it is a fact of observation that a small puff of smoke begins to diffuse under the influence of the smaller eddies at first and the initial enlargement is not very great, but later, as the individual particles become more separated, their relative motion is influenced by larger and larger disturbances, and the rate of growth increases accordingly. In other words the eddy diffusivity is a function of the size of the diffusing cluster. For a more detailed account of this point the reader is referred to original papers by L. F. Richardson[4] and O. G. Sutton[5]. If we consider an infinite number of diffusing clusters, all interacting, which is virtually the state of affairs existing in other régimes, this effect evens out and it is permissible to consider the diffusivity as a function of position as distinct from separation. In practice the dependence of eddy diffusivity on the size and motion of the individual eddies is empirically resolved into considerations of temperature lapse, surface roughness, wind velocity, velocity profile and so on.

Atmospheric fluctuations.—The fact and the importance of the fluctuations of atmospheric properties is now well established, and some explanation of their origin must form an integral part of any theory of turbulence. For wind velocity, the eddy velocities may, at times, be almost equal in magnitude to the mean value $\bar{u}$, although the average value of u' is only about 15 per cent. of the mean (Best[6]). The cause of these eddies is still something of a mystery; topographical effects, surface friction, buoyancy and viscous forces are all involved; but, taking the atmosphere as we find it, this almost continual activity must be reflected in other atmospheric properties. If such a property were conserved indefinitely during the motion as envisaged by transport-length theories enormous local variations of θ would result. However, molecular diffusion is constantly striving to destroy the anomalies; it is only the fact that molecular diffusion is slow by comparison with eddy diffusion that makes them at all possible. For general interest a temperature trace typical of the type of synoptic situation described is given in Fig. 1.

It was taken from the original paper by Priestley and Swinbank, and was recorded by means of a special sensitive thermocouple with very little lag, an initial difference of temperature between instrument and atmosphere being reduced by 90 per cent. in 5 seconds. The variations show a distinct period of about two minutes with a maximum amplitude of about 2·5°C., which would be faithfully reproduced by the instrument, and numerous minor fluctuations of a period of 5–10 seconds, about 0·5°C. in amplitude—occasionally much more—which would only represent about half the true amplitude, so

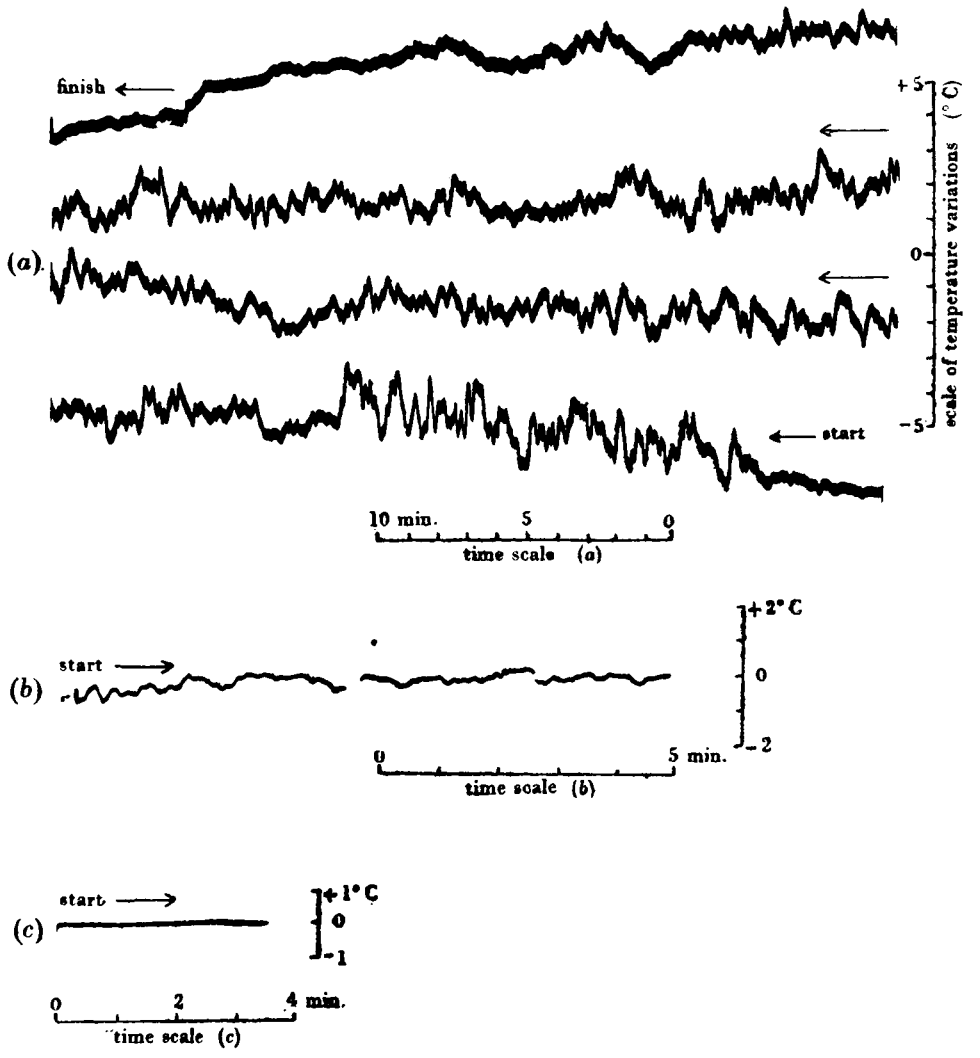

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FIG. I—VARIATION OF TEMPERATURE

Recorded by a sensitive thermocouple thermograph at Cardington, Bedfordshire, (*a*) at 4 ft. 6 in. above ground, 1450 to 1650 G.M.T. June 27, 1945, with air in rear of cold front, northerly wind 6–10 m.p.h., variable amounts of cumuliform cloud, 9 tenths at start, clearing gradually to 5 tenths; (*b*) at 3,700 ft., 1500 G.M.T. on August 3, 1945, a clear, hot summer afternoon with little wind; (*c*) at 3,000 ft., 1400 G.M.T. on September 11, 1945, dull and overcast with moderate southerly winds (marked advective cooling of air).

that an absolute range of about 3·5°C. is entailed. The authors are of the opinion that it is impossible to explain these fluctuations without postulating transport lengths of several hundreds of feet. Calculations are supplied indicating that temperature excesses as large as those observed would not survive such a long journey, and in any case, observations on drifting smoke near the ground fail to produce a travel of more than a few feet.

A full discussion of these ideas cannot be given here, but it seems that the magnitude of the fluctuations is quite consistent with small transport lengths. Best (*loc. cit.*) found that the average maximum difference of temperature in June (averaged over a period of 20 min.) between 2·5 cm. and 1·2 m. above closely cropped grass, was about 3·4°C. This value, which was for clear skies only, occurred about midday, and was for winds of 5 m.p.h. or thereabouts. Since the instrument used was nothing like sensitive enough to record fluctuations of the order of a few seconds it is practically certain that differences considerably in excess of 3·4°C. do occur and there is no difficulty in explaining by transport alone the microvariations at 4·5 ft. of 1°C. or so, recorded in Fig. 1. The conditions under which the trace was taken, namely cold air in the rear of a front being advected over a relatively warm ground in mid afternoon, makes the existence of a steep lapse rate near the surface very likely in spite of the variable cloud cover. The general impression one gets in studying the curve is of large eddies, 40–50 ft. apart, penetrating right down to, or originating from, the earth's surface and transporting temperature anomalies of the order of 0·5–1·0°C. (occasionally larger) to the datum level, and a continuously diminishing series of smaller eddies and smaller temperature fluctuations fading beyond the perception of the instrument, the whole being superimposed on broader, less erratic, variations reaching a maximum over 300–400 yd. due to the vagaries of track and past history of the air passing over the point of observation. Although these latter are not quite so obviously associated with individual eddies it is probable that large-scale convection modifies the vertical temperature gradient selectively with a consequent local accumulation of heat over such distances, and it will be noticed that as the afternoon advances there is a tendency for these periodicities to disappear. The smaller ones also have a considerably reduced amplitude with time as would be expected since the temperature lapse decreases after midday. However, the whole question of the space scale of atmospheric fluctuations horizontally as compared with the size of eddies, and their relationship to variations at a fixed point of observation, is one for further investigation.

Large temperature lapses near the ground are usually associated with steep moisture gradients, and one would therefore expect temperature and moisture excesses or deficits to appear simultaneously at the datum level on the above theory, and consequently for positive correlation between temperature and moisture content to exist near the ground. This may only be significant when some eddies, at least, originate at the surface as " bubbles " under the influence of buoyancy forces. In other circumstances and for other properties the correlation is probably small, but little is known about the subject. Another gap in our knowledge is the variation of the fluctuations with height, and their frequency distribution. They evidently increase rapidly in amplitude from the surface up to a few metres and then decrease steadily again. Aircraft reports indicate, however, that intense turbulent activity can occur at great heights,

even out of cloud, and fluctuations in the other properties are also to be expected near temperature inversions or near discontinuities of moisture and smoke.

Finally, it should be pointed out that the assumption about the magnitude and character of the anomalies θ' and θ'' may not be strictly true in all cases. In Part I the following approximate equation was deduced, viz., $\theta' = -l\delta\bar{\theta}/\delta z + \theta''$ so that, taking means over a large number of fluid elements, we get

$$\overline{\theta'} = 0 = -\bar{l}\frac{\delta\bar{\theta}}{\delta z} + \overline{\theta''}.$$

For $\overline{\theta''}$ to disappear either $\bar{l}$ or $\delta\bar{\theta}/\delta z$ must be equal to zero;* the latter is a special case which seldom occurs. Now it is quite conceivable that elements originating on one side of the datum surface may, in general, have much larger transport length than those coming from the other, so that $\bar{l}$ is not equal to zero, and neither is $\overline{\theta''}$, which implies a different sort of distribution of θ'' from that of θ'; probably neither is symmetrical about the mean value. An example of this is the streaming of air from a heated surface under conditions of light winds and great instability, in which case $\bar{l} > 0$, and $\overline{\theta''} < 0$. Convection in general presents a similar picture, in which upward transport has a longer fetch than downward transport. However, in strong winds with vigorous mechanical turbulence, the assumption seems reasonable enough; the absence of marked convection in high winds is well known.

Pressure fluctuations.—Pressure is another element which is constantly varying and although the variations are small they are of considerable importance in the theory of turbulence since they may influence the vertical transport of momentum. An elementary volume of fluid can be brought to rest horizontally by the shifting pressure gradients long before it has lost its excess temperature, say, or can retain its excess velocity long after. The average effect is unknown, but it was such considerations that led G. I. Taylor[7,8] to suggest that vorticity, which is unaffected by the local variations of pressure in two-dimensional flow, and not momentum is conserved during the motion, and the relative merit of the two approaches has still not been decided conclusively.

Pressure changes in a compressible fluid produce corresponding changes of temperature whose frequency should form a continuous spectrum from one every few minutes to thousands per second corresponding to sound vibrations, but their effect on the eddy diffusivity may even out in the long run. It would be interesting to correlate pressure with temperature for these micro-variations, and to determine the contribution of the variations of the former to those of the latter, but such an event must await the development of suitable instruments. The largest fluctuations in temperature are presumably due to mixing, compression and differential surface heating operating simultaneously. Since they are, apparently, not entirely caused by eddy motion the expression "temperature anomaly" was adopted instead of "eddy temperature" in Part I. For other properties, in view of the absence of any obvious correlation between them and the eddy velocity, and for more general usage, a similar nomenclature is preferred.

*If terms such as $l^2\delta^2\bar{\theta}/\delta z^2$ are included for exactness, the argument still applies; in fact, the discrepancy is worse when $\delta^2\bar{\theta}/\delta z^2$ is positive.

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AUSTRALASIAN ANTARCTIC EXPEDITION, 1911–14*

Under the leadership of Sir Douglas Mawson

Meteorological data from this expedition have already been published in volumes III, IV and V of this series many years ago (1929–39) and widely used in the technical literature on Antarctic meteorology. For geographical details the reader may refer to another earlier volume (Series A, Vol. I, 1942), which is copiously illustrated. The appearance of these further volumes devoted to theoretical discussion and interpretation by so eminent a meteorologist as Dr. Kidson, whose lead in the introduction of modern Norwegian methods of analysis in Australia and New Zealand is well known, will be of interest to all who follow this branch of the subject and to others concerned with the geographical and glaciological problems of the Far South.

Dr. Kidson was well fitted to undertake this work through long years of interest in Antarctic meteorology as well as through his official contacts as Director of the Meteorological Office of his native New Zealand and in earlier years in Europe, the United States and Australia. His outstanding ability in terrestrial physics was acknowledged in his election as a Fellow of the Royal Society of New Zealand. At the date of his untimely death in 1939, his work, which is reviewed here, was almost finished except for an introductory chapter, which has been deliberately left untouched.

The observation bases established by this expedition were near the coast of Antarctica in 95°E., on the edge of the Shackleton ice-shelf just seaward of the Queen Mary Land coast, and in 143°E. amongst some rock outcrops in Commonwealth Bay, Adélie Land, at the foot of the great Antarctic ice-cap, and on Macquarie Island in the Southern Ocean at 54°S. 159°E. The observations cover 11½, 22½ and 35 months respectively at these stations; a gap in the Macquarie Island series in 1914 was caused by the tragic disappearance of the relieving ship with all hands. For the twelve months covered by the daily weather charts, observations were also available from Scott's base at Cape Evans in the Ross Sea and from the various voyages of the expedition ships *Aurora* and *Terra Nova*.

Some readers will find the retention of the original units of pressure in inches of mercury and temperatures in degrees Fahrenheit awkward in making com-

*Scientific Reports, Series B, Vol. VI; *Discussion of observations*, by E. Kidson. 8vo. 12 in × 9½ in., pp. 121, *Illus.* and Vol. VII: *Daily weather charts*, by E. Kidson. 8vo. 12 in. × 9½ in., pp. 31, *Illus.*, including 365 charts. Tennant, Government printer, Sidney, New South Wales. 1946 and 1947. Price 20*s.* and 40*s.*

[*To face p.* 108

Photograph by R.A.F.

CUMULUS TOPS SPREADING OUT INTO ALTOCUMULUS

Taken from 29,000 ft. over 40° 45′ N. 05° 20′ E., 1222, September 22, 1943.

Photograph by R.A.F.

LAYER OF ALTOCUMULUS WITH CUMULUS TOPS PROTRUDING

Taken from 29,000 ft., over Montides, 1515, October 2, 1943.

Photograph by R.A.F.

STRATOCUMULUS

Taken from 9,000 ft. looking north-west over Lancashire (53° 30′ N. 2° 40′ W.) at 1118, July 27, 1945.

Photograph by R.A.F.

A NARROW LANE BETWEEN TWO LAYERS OF STRATOCUMULUS

Taken from 6,000 ft. looking north-east over Oxford, June 2, 1944.

WAVE FORM OF CLOUDS IN THE LEE OF MT. EREBUS, AT SCOTT'S BASE IN THE ANTARCTIC, OCTOBER 22, 1911

MOUNT EREBUS IN THE ANTARCTIC, OCTOBER 22, 1911

EREBUS SMOKE, SEPTEMBER 26, 1912

parisons. The isobar spacing on the charts of one tenth of an inch corresponds to about 3·4 mb.

The actual values, having been published earlier, add nothing new, though Kidson's comments are interesting. Macquarie Island's mean temperature (39·8°F.) is slightly above the average for the latitude in the southern hemisphere, whereas Kerguelen (38°F.) in 49½°S. 70°E. (Indian Ocean sector) is decidedly cold and points in 65°S. west of Graham Land have given temperatures which are decidedly warm for their latitudes. The differences between different longitudes in the southern hemisphere are greater than has often been supposed, and Kidson remarks (Vol. VII, p. 17): " Over the southern hemisphere as a whole . . . the symmetry (of the general atmospheric circulation), though much greater than in the northern, is far from perfect." This awareness of longitudinal differences in climate comes to light in Kidson's discussion of the temperature conditions favouring glaciation in Kerguelen and elsewhere. Another symptom is the prevailing north-westerly winds at Macquarie Island and the relative absence of icebergs in that sector of the Southern Ocean, south of the Tasman Sea. The north-westerly stream of warm air sweeping around the southern side of the South Australian and Tasmanian anticyclones is now believed to steer the frontal storms in this sector, which is one of the stormiest in the Southern Ocean, south-east towards the Wilkes Land coast and into the Ross Sea; it is a sector where the pack-ice fringe off the coast of Antarctica is exceptionally narrow; and at Commonwealth Bay, thanks partly to the fierce katabatic gales affecting the actual shore, there is open water right up to the coast at all times of the year.

The generally low level of atmospheric pressure everywhere in the Far South is amply borne out by these expedition results (means: 986·5 mb. at Queen Mary Land base, 988·2 mb. at Commonwealth Bay, and 998·7 mb. at Macquarie Island), and Kidson considers that the absolute maximum of 1030·5 mb. at Commonwealth Bay was probably unusually high. The highest pressure in four years at Scott's base (77½°S. 166½°E.) in the Ross Sea was 1024·4 mb. The lowest values recorded were about 940 mb. at each station.

The anticyclonic series which gave the 1030 mb. reading at Commonwealth Bay between September 1 and 3, 1912, is one of the most interesting to follow amongst Kidson's charts in Volume VII, showing how a subtropical centre of high pressure moved south or south by west on an abnormal track from eastern Australia directly towards this Antarctic station; but one is left with the impression that this centre more likely went on farther south and south-west into Antarctica instead of collapsing and vanishing eastwards as shown by Kidson on the 4th and 5th. This revision is suggested by the continuance of generally high pressures over Antarctica for the rest of that month, and indeed the following days show no westerly wind at the Queen Mary Land base and no northerly wind at Scott's base, where even the volcanic smoke of Mt. Erebus at 13,000 ft. was drifting from west, south-west or south until the 8th.

Diurnal pressure variations were detected by Kidson using harmonic analysis, the 24-hour term amounting to 0·04 mb. at Commonwealth Bay, 0·05 mb. at Scott's base, 0·17 mb. at Queen Mary Land and 0·68 mb. at Macquarie Island. Data were hardly adequate for any analysis of annual variation of pressure, but Kidson's discussion of the total pressure gradient over the width of the Southern

Ocean between Tasmania and Adélie Land reaching its maximum in October and then falling off rapidly to give the quietest conditions of the whole year in late November and December fits the known facts.

Of aperiodic variations it may be noted that Kidson discovered a tendency for the culminating maximum of pressure at Macquarie Island with the passage of Australasian anticyclones to come about the time of the evening diurnal maximum. This may be of importance in the general study of anticyclones. The greatest changes of pressure in 24 hours were rises of 55 mb. at Macquarie Island and 41 mb. at Commonwealth Bay.

There is some discussion of Simpson's theory of Antarctic pressure surges. Kidson stresses the difficulty of applying periodogram analysis to barograms, since waves of small amplitude may be missed, especially during summer when the amplitude is normally small. The results of such trials are not very convincing. For the Queen Mary Land base it is possible to deduce mean periods of pressure surges of 115 or 153 hr. according to choice, the latter figure actually agreeing with Simpson's figure for Scott's base at McMurdo Sound. Similar results can be got from the Adélie Land records, whilst for Macquarie Island periods of 136 or 183 hr. might be deduced. These figures are quite comparable with the mean period between successive anticyclones over Australia or Bergeron's figure for the frequency of rejuvenation of the Azores high. All such computations of averages however are liable to be confused and rendered inaccurate by the inclusion of non-anticyclonic periods and abnormal situations of some length. On the whole it seems that the pressure changes in the Antarctic dovetail with the frontal processes of depressions moving over the Southern Ocean and are in some way complementary to the anticyclonic developments in the subtropical high-pressure cells which steer the depressions. Kidson's remark is that " while agreeing in the main with Simpson's description of the actual processes I do not think it necessary to introduce a new type of pressure wave . . ."; and this will probably be the experience of any who visit those regions and apply modern forecasting techniques in them.

Commenting on the cloud observations Kidson draws attention to the frequency of lenticular cloud observations near the coast of Antarctica. He points the finger of doubt however at the rather frequent observations of cumulonimbus, saying (p. 99, Vol. VI) that " these clearly do not refer to true cumulonimbus . . ."; in this Kidson is almost certainly wrong, since large cumulonimbus is frequently seen by the whaling ships near the coast of Antarctica and tops estimated at 17,000–20,000 ft. are recorded in the *Balaena* observations (1946–7) at the coast in 112° E. Our theories of Antarctic weather must be adjusted, if need be, to take account of this fact. Cumulonimbus phenomena were expectedly frequent at Macquarie Island, where hail fell on over 80 days a year. The island has a dismal climate, which is fairly typical of the " fifty " latitudes in the Southern Ocean: 63 per cent. of the observations gave overcast skies, mostly with cloud on the hills, of which the highest reached about 1,400 ft.; its annual sunshine total of 380 hr. contrasted with 1,530 hr. at Adélie Land.

The most impressive figures among the observations are undoubtedly those for wind at Commonwealth Bay. These fierce katabatic winds, which blow almost constantly from S'E. and gave an annual mean of 42·9 m.p.h., must be partly controlled by topographical convergence. Much has been written about this place as the " home of the blizzard ", yet it is strange how little

description is to be found of any topographical feature which could cause funnelling. Nevertheless it is stated that the observed wind strengths were stronger than is believed to be typical even of this stretch of the coast. It is probable that the explanation must rest in part upon the unknown geography of the interior. The strength and persistence of these winds and the prevalent drift of the lower cloud, also from south-east, do not favour the idea expressed in the charts that depressions commonly pass inland over this station and cross Victoria Land into the Ross Sea, although there are some grounds for thinking that depressions occasionally cross the coast elsewhere.

In an interesting discussion of the difficulties of measurement and estimation of snowfall over Antarctica, Kidson wisely avoids any method based on the assumption that the amount accumulating must be equal to the amount of ice carried out to sea. Such an assumption would ignore the evident wasting of the ice-cap now going on. By another method of estimation Kidson arrives at about 4-in. equivalent rainfall per annum as a typical figure for the coastal regions of Antarctica and slopes below 2 Km. This figure is of the same order as measurements made by more orthodox methods on whaling ships operating near the coast in the summer season and figures obtained for north-east Greenland. In the high interior precipitation must be less. No rain at all fell at Commonwealth Bay, though frozen rain or drizzle was not uncommon; rain is not unknown in some other parts of Antarctica.

The charts in Volume VII are so extremely good in their tropical and subtropical sections over Australasia, where the detailed frontal analysis of tropical cyclones is both new and convincing, that one hesitates to say that the sections over the Southern Ocean and Antarctica are less convincing. One does feel however that the more recent work of Palmer and Ramage* on these regions is really more successful than Kidson's pioneering attempt. Kidson was unfortunate in his assumption, however natural at first sight, that systems affecting Queen Mary Land in 95°E. must eventually affect the bases farther east. We now have evidence of a distinct change of régime in the atmospheric circulation in the higher southern latitudes east and west of about the hundredth meridian. Points west of 100°E. come under the influence of systems circulating southwards from the Indian Ocean and often recurving towards the west in their latter stages. Kidson made it a basic assumption that such westward components of motion could never arise in the Far South. He also seems to have gone too far in deliberately ignoring the katabatic winds and airflow within the Antarctic continental air masses in drawing his isobars over the coastal regions and interior. These air masses are not always shallow, and balloon and nephoscope upper-wind observations show that the easterly wind components which prevail in the surface winds at the coast sometimes reach up to over 10,000 ft. both in anticyclonic and cyclonic situations.

In spite of these criticisms the importance of Dr. Kidson's pioneering effort in the application of normal circulation theories and methods of analysis to the Antarctic must be recognised. This approach is now generally employed.

H. H. LAMB

*PALMER, C. E.; Synoptic analysis over the southern oceans. *Prof. Notes N.Z. met. Off., Wellington*, No. 1, 1942.

RAMAGE, C. S.; The atmospheric circulation of the Ross Sea area. *Prof. Notes N.Z. met. Off., Wellington*, No. 2, 1944.

METEOROLOGICAL OFFICE DISCUSSION

The Meteorological Office's Monday evening discussion on March 22 was devoted to the consideration of a paper entitled " The influences of shelterbelts on the microclimate of the adjoining territory " by B. A. Bodrov*. The discussion was opened by Mr. R. W. Gloyne who, after pointing out that the paper dealt with some observations taken in the months of July and August during two years over an area with uniform topography near Saratov, sketched briefly the type of meteorological problems which arise in studies of phenomena of this nature. The subject is of fundamental importance in semi-arid regions and is directly related to methods of controlling soil erosion.

After explaining the lay-out of the experiment and the various control and calibration tests undertaken, the influence of a shelterbelt on the wind velocity, temperature, humidity, and evaporation from open water surfaces in the " protected " zone was illustrated by graphs constructed from the original data. The very appreciable percentage reduction in wind velocity for a distance leeward of about 30 times the height of the belt was evident, as were also the " second-order " effects introduced by the absolute value of the particular meteorological element, the height of the barrier and the degree of permeability or penetrability offered by the belt to the airflow. There was evidence also that in certain circumstances measurable effects were to be found at far greater distances from the belt (up to 100 times its height or more).

It was chiefly, however, in the effects on evaporation (as measured by the loss of water from an exposed free surface in a small evaporimeter) that the effectiveness (or " efficiency ") of a shelter belt can be most clearly demonstrated, and these results were held to explain the marked increase in crop yields obtained in semi-arid areas by utilising the protective properties of belts of closely planted trees.

The Director in throwing open the meeting to discussion emphasised the great opportunities presented to the meteorologist in the field of agricultural science, opportunities which so far had been inadequately taken in this country, and he went on to suggest as a typical problem the determination of the effect of unit change in any chosen climatic element on the rate of growth, etc., of field crops. With Dr. Brooks, who pointed out that the Climatological Branch are now making plans for investigation in eco-climatology, the Director expressed surprise at the magnitude of the effects recorded in the paper. Mr. Hogg commented on the fact that with so many variables it was desirable to isolate and study one at a time, and was particularly concerned at the complexities introduced by the very varied crop cover over the area chosen for investigation. Dr. Glasspoole considered in some detail the variations in the catch of a rain-gauge under different conditions of exposure, whilst Dr. Robinson inquired whether the increased moisture evident in the protected zone was at the expense of neighbouring protected areas. Mr. Drummond then pointed out that the extent of the instrumental variance recorded in control tests rendered the results obtained for humidity of somewhat doubtful significance, and Mr. Sawyer suggested that the higher humidity in the protected zone might be attributable to a greater drain on soil moisture reserve due to the increased

*A publication of the All Union Scientific Research Institute on silviculture and improvement of farmland by forestation, Moscow, 1935. English abstract by R. W. Gloyne, London, 1948.

transpiration in the more turbulent air flow to the lee of the barrier, and finally Mr. Crawford stressed the need for well-planned experimental designs for work of this nature.

In the course of the discussion and in his closing remarks Mr. Gloyne agreed that it would be unjustifiable to generalise too readily from the results obtained in one type of climate and with one type of experimental lay-out. It was, however, true that investigational work elsewhere (particularly in the U.S.A.) gave effects of the same order of magnitude; but on the other hand he fully agreed that many carefully designed experiments under our conditions were essential before we could speak with confidence concerning the effects of similar belts on eco-climate and consequently on crop yields, etc., in more equable climates.

METEOROLOGICAL RESEARCH COMMITTEE

The 54th meeting of the Committee was held on March 18, 1948.

In order that the Committee may be able to devote more time to considerations of the general policy to be followed in meteorological research it was decided to form three sub-committees, each of which will be responsible for advising on investigations dealing with problems in one part of the research programme and for examining reports on these problems. The three sub-committees correspond to the three parts of the research programme and are as follows:—

Instruments Sub-Committee	Chairman, Prof. P. A. Sheppard
Synoptic and Dynamical Sub-Committee	Chairman, Sir Charles Normand
Physical Sub-Committee	Chairman, Prof. G. M. B. Dobson

Parts I and II of the Research Programme were revised, Part III being left for revision by the Physical Sub-Committee.

The first meeting of the Physical Sub-Committee was held on April 8, 1948.

Part III of the Research Programme was revised.

A report dealing with the variation of mean wind speed in the lowest 350 ft. of the atmosphere was discussed. During this discussion it was agreed that the question of whether the index in the power law, representing the variation of wind with height, can exceed unity is of fundamental importance. The report under consideration was at variance with another unpublished report on this point and the matter was referred back for further examination.

ROYAL METEOROLOGICAL SOCIETY

At the meeting of the Society held on March 17 at 49 Cromwell Road, Prof. G. M. B. Dobson, President, in the Chair, the following paper was read:—

O. G. Sutton—Convection in the atmosphere near the ground

The earlier theories of turbulence, Prof. Sutton pointed out, regarded the vertical transfer of heat and momentum as being carried on by eddies set up as the wind blows over a rough surface. The vertical velocities in these eddies arise solely from the fluctuations in the horizontal wind. Such a theory fails on clear sunny days of light wind when convection currents are set up over

the heated parts of the ground. These upwards currents may be regarded as convectional eddies, composed of upward moving bubbles or streams of heated air which are gradually dissipated by mixing with their surroundings. The intensity of the turbulent convection currents is determined by the balance between the rate of dissipation by breakdown of the heated mass into smaller eddies and the rate of loss of potential energy. Using some results obtained by Taylor, Prof. Sutton shows that the rate of loss of kinetic energy in turbulent motion is proportioned to w'^3/l_H where w' is the upward eddy velocity and l_H is a length determining the scale of the turbulence. Equating this quantity to the rate of loss of potential energy of the rising air we then obtain

$$w' \propto l_H \sqrt{\frac{1}{T}} \left(\frac{\delta T}{\delta z} + \Gamma \right).$$

The upward moving bubbles of heated air give rise to temperature fluctuations of magnitude T' at any level and Prof. Sutton defines the quantity l_H, which measures the scale of the turbulence, by the equation

$$T' = - l_H \left(\frac{\delta T}{\delta z} + \Gamma \right).$$

By analogy with frictional turbulence we also have an eddy coefficient of conductivity K_H equal to $\overline{w' l_H}$.

With these definitions the upward flux of heat is given by

$$q = - c_p \rho K_H \left(\frac{\delta T}{\delta z} + \Gamma \right),$$

where c_p, ρ have the usual meanings. If it now be assumed that q is constant with height we can deduce

$$\begin{array}{rl} & w' \propto l_H^{1/3} \\ \dfrac{\delta T}{\delta z} + \Gamma & \propto l_H^{-4/3} \\ & T' \propto l_H^{-1/3} \end{array}$$

and the problem is reduced to that of finding the relation between l_H and z.

Before considering the variation of l_H with height, however, Prof. Sutton showed that, using the exact equation

$$- \frac{\delta q}{\delta t} = c_p \rho \frac{\delta T}{\delta t}$$

and values of $\delta T/\delta t$ obtained by Johnson and Heywood at Leafield, the variation of q with height during the midday hours of a fine summer day is so small that it can be neglected, at any rate up to $z = 100$ m., and the assumption that q is a constant is therefore justified.

Turning now to the variation of l_H with height Prof. Sutton used some simultaneous measurements of T' and $\delta T/\delta z$ also obtained at Leafield by Johnson and Heywood. We have seen above that $T'/(\delta T/\delta z + \Gamma)$ is proportional to l_H and by this method Prof. Sutton obtained

$$l_H \propto z^{1.35}$$

and hence

$$\begin{array}{llll} K_H \propto z^{1.8}, & \dfrac{\delta T}{\delta z} + \Gamma & \propto z^{-1.8} \\ w' \propto z^{0.45}, & T' & \propto z^{-0.45} \end{array}$$

A logarithmic plot of $\delta T/\delta z + \Gamma$ against height showed that $\delta T/\delta z + \Gamma$ varies as $z^{-1.75}$ in satisfactory agreement with the result deduced above.

Considering next the question of whether buoyancy effects need to be taken into account Sutton pointed out that Elias found the velocity and temperature profiles above a heated plate in a speed of 35 m./sec. in a wind tunnel were practically identical so that in strong winds the transfer of heat and momentum are brought about by the same mechanism. There are no simultaneous observations of wind and temperature profiles in the atmosphere but the usually accepted theory of the variation of wind with height (Schmidt, Ertel, Sutton, Frost) gives a diffusion coefficient of the form z^{1-p}, where p is between 0 and 1, which does not agree with the Leafield observations. Hence, when the temperature lapse rate is steep and wind light, buoyancy must be taken into account.

Finally Prof. Sutton proposed a mathematical model for convective processes in which a thin slab of heated air was supposed to rise under buoyancy forces expanding as it did so. For the details reference must be made to the original paper. Without claiming very exact correspondence with reality Sutton is able to show that the motion of the slab produced a heat flux in close accord with observations.

Mr. Best, opening the discussion on the paper, said he was not satisfied that the flux of heat by radiation could be neglected, as was implicitly done by Sutton, in equating the total flux whose gradient corresponded to the time variation of mean temperature with the flux given by the formula $-K_H c_p \rho(\delta T/\delta z + \Gamma)$. He confirmed the difficulty of obtaining values of the fluctuations of temperature from recent efforts of his own to read them from the records now being made on a tower at Rye.

Sir Nelson Johnson said that when he was working on these problems the idea that bubbles of heated air produced a heat transfer in addition to that due to mechanical turbulence had always been in his mind. He was very interested to see Sutton's use of his observations. He regretted the Rye records did not show fluctuations.

Mr. Batchelor referred to the fact that the conditions favourable for free convection with rising currents of hot air were also suitable for patterned convection of the Bénard cell type and suggested it would be worth investigating to see if patterned convection did occur. He noted some of the values of l_H were rather larger than the height above ground of the point to which they referred, which agreed with the fact that the temperature fluctuations could only be accounted for by supposing the air producing them to come right up from the hot ground.

Prof. Sheppard doubted whether there really was any difference between the transfer of heat and the transfer of momentum; an eddy transported both impartially.

Dr. Slater said much larger fluctuations than those quoted had been measured under similar conditions by Höhndorf at Darmstadt.

Dr. Robinson considered radiation effects must be taken into account and described work of his own which showed that for the first metre above the soil the radiative flux of heat was almost equal to the convective flux.

Prof. Sutton, replying to the discussion, regretted very much that the Rye tower records gave no information on fluctuations and agreed with Dr. Robinson that radiation needed much more attention.

ROYAL STATISTICAL SOCIETY

At the meeting of the Study Section of the Royal Statistical Society on March 10, a discussion on the use of statistical analysis in meteorology was opened by Miss N. Carruthers. Reference was made to the estimation of normal values, the fitting of theoretical distributions of frequencies* and the effect of persistence in meteorological elements. The persistence effect requires a modification of the well-known expressions for standard error, for these apply only to distributions of independent observations. Two other main topics were correlation and the analysis of periodicities. Among other things, the former had been applied to the investigation of solar and terrestrial relationships and to the seasonal forecasting of weather and crop yields, and the latter had been used to compare meteorological and solar cycles and to review the choice of standard period for normals.

The wide demand for meteorological statistics was emphasised by several " consumers " who, in pointing out their particular needs and their particular lines of investigation, added much to the interest of the discussion. The problem of estimating ground temperatures over a long length of underground cable was raised in connexion with the resistance of telephone cables; weekly forecasts of air temperature for the planning of fuel consumption were the principal need of the Gas Light and Coke Company; and upper air data were required by British European Airways, particularly wind frequencies and forecasts of precipitation static. The Ministry of Health had found growth in height of children to be related to the number of hours of sunshine, and they were now investigating the effects of climate and weather on the incidence and spread of infantile paralysis. The London Transport Board, in connexion with sporting events and Bank Holidays, were concerned with planning for heavy passenger traffic governed largely by weather conditions. In this, a knowledge of the approximate dates of annual recurrence of particular types of weather† had already proved helpful. These instances, of course, form only a small sample of the applications of meteorology but they are sufficient to give some indication of the wide range of problems involved.

N. CARRUTHERS

LETTER TO THE EDITOR

Unusual condensation trails

I was particularly interested in the report by Mr. Aanensen in your January issue on the formation of an unusual condensation trail (a trail forming initially at the propellors).

I am happy to be able to advise Mr. Aanensen that there are some further authenticated occurrences of this phenomenon in existence. Probably the best report is one concerning a flight made at South Farnborough on March 13, 1934, by (I think) the late W./Cdr. (then F./Lt.) Stainforth who was very interested

*BROOKS, C. E. P.; The numerical basis of climate. *Met. Mag., London*, **76**, 1947, pp. 9, 36, 56.
†BROOKS, C. E. P.; Annual recurrences of weather: " Singularities ", *Weather, London*, **1**, 1946, pp. 107, 130.

in these occurrences and who was a very careful and critical observer of any phenomenon he set out to investigate. He reported " mist streaming from the airscrew at 8,500 ft., sufficiently dense to obscure an object fitted on the top plane." Other reports spoke of " thin flakes of ice-like transparent ' LUX ' coming from the airscrew."

At that time, 1934–5, practically all condensation trails, then referred to as " alto-cumulus formed by aeroplane "* were caused by aircraft flown from R.A.E., Farnborough, who alone flew regularly at the heights where these trails most frequently occur. The aircraft, of course, were all single-engined biplanes, due, as we were destined to discover, for rapid replacement by the monoplane.

In the case quoted the aircraft was a Bulldog with long exhaust pipes trailing back under the fuselage (the exhaust gases were thus precluded from taking any part in the initial formation) and the pilot would be located in the middle of the fuselage, aft of the wings.

Mr. J. S. Smith and myself collected and sifted a goodly quantity of information, relating to these condensation trails, brought in by the pilots and observers at the R.A.E., whose interest in the phenomenon was as great as ours. It was because we had among the comparatively few occurrences some cases in which the trails undoubtedly commenced in circumstances which precluded any possibility of the exhaust gases contributing to the initial formation, that we felt constrained to invoke in our report the pressure reductions caused by the airflow in the immediate vicinity of the fuselage and elsewhere as contributory causes of the formations, as well as to account for the twin character of the trails.

It was also found that trails were formed readily in cloud-free air when there was an occlusion in the vicinity of the British Isles, and also near the boundary of an old cloud system as shown by C. K. M. Douglas in the case reported by Mr. Aanensen.

Unfortunately the trails often occurred at higher levels than those attained by the now famous meteorological flight at Duxford, so not only were we often not able to relate the formation to the tephigram but we certainly had no humidity data for the levels.

F. H. DIGHT

BOOKS RECEIVED

On graduation of data. By Dr. H. J. De Boer. Koninklijk Magnetisch en Meteorologisch Observatorium te Batavia. Verhandelingen No. 33. Size $9\frac{3}{4}$ in. $\times$ $6\frac{1}{4}$ in. pp. 20. Surabaya, 1947.

WEATHER OF MARCH 1948

Anticyclones influenced the weather over the British Isles during most of the month, which was one of exceptionally high mean pressure. During the first week the centre of highest pressure was to the eastward, but on the 8th and 9th was over France. On the 10th it was to the south-west of Ireland, and from the 11th to the 14th over or near to the British Isles. From the 15th to the 22nd very deep depressions near Iceland brought a spell of southerly to westerly winds over the British Isles, but by the 23rd a new anticyclone had developed

*See *Met. Mag., London*, **66**, 1931, p. 66; **67**, 1931, p. 89; **72**, 1937, p. 94.

over England. As this system drifted away to Germany there was a spell of fine quiet weather, with winds mainly from between S. and E. changing to a period of very disturbed weather during the last two or three days of the month under the influence of secondary depressions associated with a deep depression near Iceland. There was an exceptionally rapid fall of the barometer on the 31st, and by midnight pressure was down to 954 mb. at Tiree.

The map of mean pressure shows an area with pressure above 1025 mb. covering most of Europe southwards of Scandinavia, and including the western Mediterranean and southern England. Mean pressure was below 1000 mb. between Iceland and Spitsbergen. Pressure was above normal generally over Europe and the Mediterranean, by as much as 15 mb. in south-east England and Holland, and from 10 to 15 mb. below normal in Greenland.

The weather over the British Isles was warm and sunny, it was also dry except over considerable areas in the north-west. Mainly anticyclonic conditions prevailed until the closing days, though troughs of low pressure affected the weather at times, particularly in the north-west. Mean pressure greatly exceeded the average, especially in the south-east; at Oxford the mean for the month was only 0·010 in. below the previous record for March, which occurred in 1929. Considerable fog developed during the first six days and a widespread, severe gale was reported on the 31st.

Mean temperature was exceptionally high; in England and Wales, apart from March 1938, it was the highest for March since before 1901; in Scotland and Ireland there were two higher means, namely 1938 and 1945. It was very warm in England and Wales on the 9th, when temperatures of 70°F. or above were registered at numerous stations. Rainfall exceeded the average over much of the western half of the Scottish mainland, over part of Northern Ireland and locally in Cumberland and Snowdonia. On the other hand less than one quarter of the average was measured in a coastal belt from North Berwick to Morpeth (Northumberland) and from Gordon Castle to the northern tip of Aberdeenshire. Heavy falls of rain occurred in the north-west on the 7th and 20th and, more generally, on the 31st; for example 3·36 in. at Blaenau Festiniog (Merioneth) and 2·58 in. at Ardgour (Argyll) on the 7th, 2·58 in. at Glenquoich (Inverness) on the 20th and 4·28 in. at Thirlmere (Cumberland) and 4·24 in. at Haweswater (Westmoreland) on the 31st.

The duration of bright sunshine was much in excess of the average in England and Wales and exceeded the average in Northern Ireland and, on the whole, in Scotland, though a few places in the latter country received rather less than the average.

The general character of the weather is shown by the following table:—

	Air Temperature			Rainfall		Sunshine	
	Highest	Lowest	Difference from average daily mean	Percentage of average	No. of days difference from average	Percentage of average	Percentage of possible duration
	°F.	°F.	°F.	%		%	%
England and Wales ..	75	22	+4·7	54	−8	136	44
Scotland	71	20	+4·6	88	−4	114	34
Northern Ireland ..	67	26	+5·5	91	−4	119	35

RAINFALL OF MARCH 1948

Great Britain and Northern Ireland

County	Station	In.	Per cent of Av.	County	Station	In.	Per cent of Av.
London	Camden Square ..	·57	31	*Glam.*	Cardiff, Penylan ..	1·77	56
Kent	Folkestone, Cherry Gdns.	·90	41	*Pemb.*	St. Ann's Head.. ..	2·15	79
,,	Edenbridge, Falconhurst	·99	40	*Card.*	Aberystwyth	1·22	45
Sussex	Compton, Compton Ho.	1·14	41	*Radnor*	Bir. W. W., Tyrmynydd	3·62	67
,,	Worthing, Beach Ho. Pk.	·86	45	*Mont.*	Lake Vyrnwy	4·07	89
Hants.	Ventnor, Roy. Nat. Hos.	·67	33	*Mer.*	Blaenau Festiniog ..	8·84	102
,,	Fordingbridge, Oaklands	1·10	47	*Carn.*	Llandudno	1·39	68
,,	Sherborne St. John ..	1·08	48	*Angl.*	Llanerchymedd ..	2·15	72
Herts.	Royston, Therfield Rec.	·91	50	*I. Man.*	Douglas, Boro' Cem. ..	3·01	102
Bucks.	Slough, Upton	·83	47	*Wigtown*	Port William, Monreith	1·39	49
Oxford	Oxford, Radcliffe ..	·72	44	*Dumf.*	Dumfries, Crichton R.I.	2·79	93
N'hant	Wellingboro', Swanspool	·80	45	,,	Eskdalemuir Obsy. ..	4·53	92
Essex	Shoeburyness	·46	34	*Roxb.*	Kelso, Floors	·78	40
Suffolk	Campsea Ashe, High Ho.	·82	49	*Peebles.*	Stobo Castle	2·69	93
,,	Lowestoft Sec. School ..	·48	30	*Berwick*	Marchmont House ..	·63	24
,,	Bury St. Ed., Westley H.	·76	40	*E. Loth.*	North Berwick Res. ..	·43	23
Norfolk	Sandringham Ho. Gdns.	·76	40	*Midl'n.*	Edinburgh, Blackf'd. H.	1·06	54
Wilts.	Bishops Cannings ..	1·11	49	*Lanark*	Hamilton W. W., T'nhill	3·17	114
Dorset	Creech Grange ..	1·21	43	*Ayr*	Colmonell, Knockdolian	3·63	107
,,	Beaminster, East St. ..	1·52	52	,,	Glen Afton, Ayr San. ..	6·28	150
Devon	Teignmouth, Den Gdns.	1·39	53	*Bute*	Rothesay, Ardencraig ..	4·19	117
,,	Cullompton	1·21	44	*Argyll*	L. Sunart, Glenborrodale	5·41	97
,,	Barnstaple, N. Dev. Ath.	1·08	41	,,	Poltalloch	4·68	122
,,	Okehampton, Uplands	2·72	66	,,	Inveraray Castle ..	9·45	149
Cornwall	Bude School House ..	1·04	43	,,	Islay, Eallabus	4·29	112
,,	Penzance, Morrab Gdns.	1·71	53	,,	Tiree	3·39	101
,,	St. Austell, Trevarna ..	1·96	57	*Kinross*	Loch Leven Sluice ..	1·66	56
,,	Scilly, Tresco Abbey ..	1·63	62	*Fife*	Leuchars Airfield ..	·68	35
Glos.	Cirencester	1·32	57	*Perth*	Loch Dhu	8·43	128
Salop	Church Stretton ..	1·49	62	,,	Crieff, Strathearn Hyd.	2·52	79
,,	Cheswardine Hall ..	·96	45	,,	Blair Castle Gardens ..	2·11	81
Staffs.	Leek, Wall Grange, P.S.	1·19	44	*Angus*	Montrose, Sunnyside ..	·59	28
Worcs.	Malvern, Free Library	1·18	61	*Aberd.*	Balmoral Castle Gdns...	1·99	70
Warwick	Birmingham, Edgbaston	1·25	65	,,	Dyce, Craibstone ..	·87	33
Leics.	Thornton Reservoir ..	1·04	57	,,	Fyvie Castle	·57	21
Lincs.	Boston, Skirbeck ..	·50	32	*Moray*	Gordon Castle	·48	21
,,	Skegness, Marine Gdns.	·56	34	*Nairn*	Nairn, Achareidh ..	1·08	59
Notts.	Mansfield, Carr Bank ..	·65	31	*Inv's*	Loch Ness, Foyers ..	3·48	108
Ches.	Bidston Observatory ..	·77	41	,,	Glenquoich	12·26	126
Lancs.	Manchester, Whit. Park	·99	44	,,	Fort William, Teviot ..	9·18	137
,,	Stonyhurst College ..	2·63	71	,,	Skye, Duntuilm ..	3·77	86
,,	Blackpool	1·61	68	*R. & C.*	Ullapool	2·81	69
Yorks.	Wakefield, Clarence Pk.	·97	54	,,	Applecross Gardens ..	4·90	105
,,	Hull, Pearson Park ..	·61	34	,,	Achnashellach	8·53	126
,,	Felixkirk, Mt. St. John	1·01	51	,,	Stornoway Airfield ..	3·08	79
,,	York Museum ..	·67	40	*Suth.*	Lairg	2·98	96
,,	Scarborough	1·06	59	,,	Loch More, Achfary ..	6·79	105
,,	Middlesbrough.. ..	·92	59	*Caith.*	Wick Airfield	1·07	47
,,	Baldersdale, Hury Res.	2·35	76	*Shet.*	Lerwick Observatory ..	2·68	85
Nor'ld	Newcastle, Leazes Pk.	·65	32	*Ferm.*	Crom Castle	3·23	104
,,	Bellingham, High Green	1·70	58	*Armagh*	Armagh Observatory ..	2·59	110
,,	Lilburn, Tower Gdns. ..	·79	30	*Down*	Seaforde	2·60	89
Cumb.	Geltsdale	1·65	59	*Antrim*	Aldergrove Airfield ..	1·47	59
,,	Keswick, High Hill ..	5·14	114	,,	Ballymena, Harryville	2·28	72
,,	Ravenglass, The Grove	2·97	96	*Lon.*	Garvagh, Moneydig ..	2·60	83
Mon.	Abergavenny, Larchfield	2·13	70	,,	Londonderry, Creggan	3·04	95
Glam.	Ystalyfera, Wern House	5·22	97	*Tyrone*	Omagh, Edenfel ..	3·64	116

CLIMATOLOGICAL TABLE FOR THE BRITISH COMMONWEALTH, NOVEMBER 1947

Stations	Pressure		Temperatures							Relative humidity	Mean cloud amount	Precipitation			Bright Sunshine	
			Absolute		Mean values											
	Mean of day M.S.L.	Diff. from normal	Max.	Min.	Max.	Min.	½ Max. and Min.	Diff. from normal	Wet bulb			Total	Diff. from normal	Days	Daily Mean	Percentage of possible
	mb.	mb.	°F.	°F.	°F.	°F.	°F.	°F.	°F.	%	tenths	in.	in.		hr.	%
London, Kew Observatory	1014·0	+0·1	61	23	50·5	40·8	45·7	+1·9	43·6	85	7·5	1·07	—1·15	13	1·9	22
Gibraltar	1019·6	+1·6	78	47	70·3	58·6	64·5	+4·5	60·4	85	4·7	2·09	—	3	—	—
Malta	1015·9	0·0	73	52	69·4	60·2	64·8	+0·9	60·7	68	5·1	0·24	—	4	7·8	76
St. Helena	1015·2	—	67	54	63·8	55·5	59·7	+1·2	55·7	96	9·4	0·74	—0·44	15	—	—
Freetown, Sierra Leone	1010·7	+1·3	88	71	84·9	76·0	80·5	+1·2	75·9	80	5·8	0·75	—4·37	8	6·9	59
Lagos, Nigeria ..	1010·5	+0·4	93	64	89·3	70·4	79·9	—1·8	76·8	83	7·7	1·63	—	5	5·8	49
Kaduna, Nigeria ..	1010·1	—	94	52	89·3	59·2	74·3	—3·6	60·7	30	4·4	0·00	—0·21	0	8·8	76
Chileka, Nyasaland	1012·2	+0·9	96	64	89·8	69·5	79·7	+2·0	68·0	53	4·3	3·04	—0·78	8	7·6	59
Salisbury, Rhodesia..	1010·5	—0·7	92	57	83·3	61·5	72·4	+2·2	61·5	51	4·9	5·19	+1·17	15	7·7	60
Cape Town ..	1014·5	—1·3	88	49	76·1	58·0	67·1	+2·7	60·4	70	4·2	0·22	—0·87	4	—	—
Germiston, South Africa	1010·1	—	92	44	80·8	57·2	69·0	—	58·1	54	4·0	2·88	—	12	9·3	69
Mauritius	1017·4	+1·3	88	62	82·2	65·7	73·9	—1·6	67·1	71	5·0	2·37	+0·61	18	9·0	69
Calcutta, Alipore Obsy.	1014·0	+0·6	92	59	87·3	64·6	75·9	+2·4	66·4	86	1·1	0·00	—0·65	0	9·2	83
Bombay	1012·9	+0·9	93	69	88·6	72·9	80·7	+0·1	72·0	80	2·2	0·00	—0·45	0	9·9	89
Madras	1013·0	+1·7	93	67	86·2	71·1	78·7	—0·2	72·1	81	4·3	2·81	—10·80	6	8·6	75
Colombo, Ceylon ..	1011·8	+1·8	90	66	87·2	71·7	79·5	—0·5	72·9	86	4·0	5·72	—6·04	7	9·3	79
Singapore	1010·1	+0·7	89	70	85·8	73·4	79·6	—1·0	76·9	85	—	8·80	—1·11	20	—	—
Hongkong	1016·8	—0·8	84	54	76·5	65·5	71·0	+1·4	64·0	69	—	0·56	—1·18	10	6·1	55
Sydney, N.S.W. ..	—	—	86	52	70·5	58·0	64·3	—2·7	58·9	65	7·1	3·31	+0·46	14	7·0	50
Melbourne	1012·8	—1·6	90	43	68·2	50·1	59·1	—2·2	53·3	61	7·5	2·02	—0·21	15	5·7	40
Adelaide	1014·1	—1·2	98	43	73·2	53·1	63·1	—3·9	55·5	54	5·5	1·18	+0·04	10	7·7	55
Perth, W. Australia	1014·9	—0·5	93	45	75·5	55·6	65·5	—0·6	58·7	58	3·1	0·49	—0·31	5	10·1	73
Coolgardie	1014·4	+1·0	96	41	81·7	54·4	68·1	—2·6	55·0	46	3·4	0·87	+0·28	4	—	—
Brisbane	1012·9	—1·7	90	57	78·6	63·2	70·9	—2·6	63·7	65	6·6	2·80	—0·93	12	7·3	57
Hobart, Tasmania ..	1012·3	+2·7	88	40	63·6	46·7	55·1	—2·1	49·8	60	8·2	1·37	—1·10	19	7·0	48
Wellington, N.Z. ..	1018·4	+6·3	74	38	63·1	49·8	56·5	+0·9	53·4	67	6·9	1·05	—2·47	7	8·5	59
Suva, Fiji	1010·3	—0·8	89	69	82·1	72·1	77·1	0·0	71·7	77	7·5	4·90	—4·89	16	6·0	47
Apia, Samoa ..	1009·2	—0·3	89	73	85·8	73·9	79·9	+1·2	77·1	79	6·6	12·92	+3·09	23	7·1	56
Kingston, Jamaica ..	1012·8	+0·4	93	71	90·1	73·3	81·7	+2·4	74·8	75	2·8	0·49	—2·54	2	9·4	83
Grenada, W. Indies	1010·5	—0·1	88	65	86·8	73·9	80·3	+0·8	76·3	76	5·0	2·43	—6·03	14	—	—
Toronto	1017·1	—0·2	58	19	43·5	32·8	38·1	+1·1	35·0	—	7·3	1·29	—1·34	7	3·6	37
Winnipeg	1015·8	—1·6	55	13	26·5	13·2	19·9	—1·4	16·9	—	6·7	0·91	—0·16	15	3·0	33
St. John, N.B. ..	1014·2	—0·4	60	18	44·4	31·7	38·1	+1·4	33·1	—	6·8	3·85	—0·56	15	3·4	35
Victoria, B.C. ..	1020·7	+4·8	57	26	48·2	36·0	42·1	—2·4	38·4	98	6·8	2·45	—2·96	16	3·3	35